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Structure and Physical Conditions in MHD Jets from Young Stars

Hsien Shang
Institute of Astronomy and Astrophysics, Academia Sinica, Taipei 106, TAIWAN
Center for Astrophysics, 60 Garden St., MS-42, Cambridge, MA 02138, USA
E-mail:shang@asiaa.sinica.edu.tw
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ABSTRACT

We have constructed the foundations to a series of theoretical diagnostic methods to probe the jet phenomenon in young stars as observed at various optical forbidden lines. We calculate and model in a self-consistent manner the physical and radiative processes which arise within an inner disk-wind driven magnetocentrifugally from the circumstellar accretion disk of a young sun-like star. Comparing with real data taken at high angular resolution, our approach will provide the basis of systematic diagnostics for jets and their related young stellar objects, to attest the emission mechanisms of such phenomena. This work can help bring first-principle theoretical predictions to confront actual multi-wavelength observations, and will bridge the link between many very sophiscated numerical simulations and observational data. Analysis methods discussed here are immediately applicable to new high-resolution data obtained with HST and Adaptic Optics.

Key Words : Jets;Herbig-Haro Objects;Young Stars and Protostellar Objects; MHD Winds;Outflows;Forbidden Lines

I. Introduction

Herbig-Haro objects (Herbig 1950,Haro 1950) are small nebulous objects that trace jet-like, collimated structures, with characteristic emission spectra of hydrogen and optical forbidden lines of [O I], [N II], and [S II], in the red wavelengths. Mechanisms that produce these phenomena play necessary roles in the making of young stars.

Whether jets alone can also drive the often associated molecular outflows has been long debated (Reipurth & Bally 2001). The morphology and the distribution of mass and momenta of these outflows argue for wide-angle winds pushing the ejecta and sweeping up materials at wide solid angles (Shu et al 1991). X-winds, by construction, are wide-angle winds, launched magneto-centrifugally near the innermost edge of the circumstellar disks of YSOs (Shu et al 1994), that expand and quickly fill space to ultimately collimate at large distances. Shang et al. (1998) demonstrated the density structure and kinematic information for an x-wind based on a semi-analytic method (Shang 1998), by computing emissions from [S II]λ6716 and [O I]λ6300 lines with uniform ionization conditions throughout the smooth flow without identifying the sources of excitation. The synthetic images for the forbidden lines show strongly cylindrically stratified structures in the center, and suggested the visual appearance of jets is an *optical illusion* out of an intrinsically very divergent flow (Shu et al 1995).

It is very compelling to learn whether conditions arising self-consistently in flows driven by magnetically interacting young star-disk systems can reproduce the many observed features known about the dynamics, morphology, and excitation conditions of jets and Herbig-Haro objects. To identify a definitive set of diagnostic tools to help probe the highly collimated jet emissions from the theoretical aspects, is the primary task. This also serves as the first test to bring a well-developed MHD model based on semi-analytic approaches into stringiest confrontation with observations. The fundamental concepts and approaches can be generalized with many multiwavelength observations, and transferred to other theoretical MHD wind/jet models, such as the many interesting numerical simulations discussed in this volume.

II. Physics Conditions and Thermal Structure of Jets

We opened new investigations of thermal structures in the MHD winds from young stars, following an earlier attempt of Ruden, Glassgold, & Shu (1990, RGS), for a cold spherical stellar wind. In RGS, they attempted a spherically symmetric model, with density, velocity and Lorentz forces enough to accelerate the neutrals to escape velocity. They found that the dominant source of heat for the gas is ambipolar diffusion associated with the magnetic acceleration, and adiabatic expansion of the wind is the most powerful cooling mechanism. However, ambipolar diffusion failed to heat the wind beyond $\sim 10\,\mathbf{R}_*$, and the plasma could be at most lightly ionized ($< 10^{-4}$). In the environment of star-disk interaction, many new processes have been discovered and identified since RGS (e.g. Shu et al 1997). In Shang et al (2001), we incorporated the processes into the self-consistent x-wind flow and made it a diagnostic package fore the jet phenomena.

New ingredients: X-rays, as observed to accompany essentially all YSOs (e.g., Feigelson & Montmerle 1999), UV photons from accretion funnels onto stars,

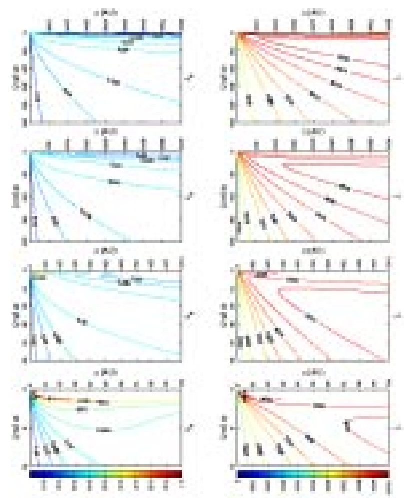

Fig. 1.— Temperature (right) and ionization (left) contours in the $\varpi - z$ plane for a fiducial case of an early but slightly revealed YSO. The units for the spatial scales are AU.

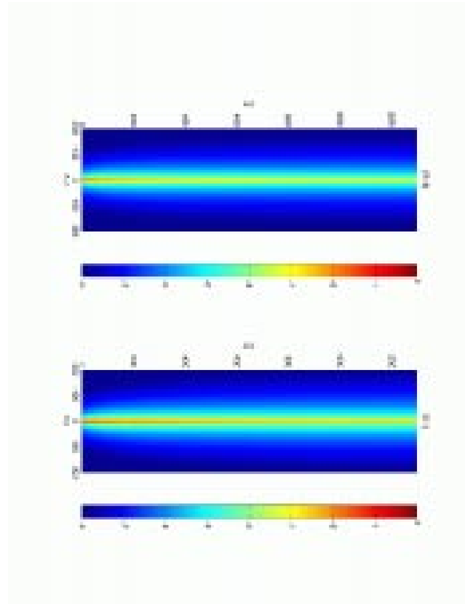

Fig. 2.— Synthetic images of the [S II] λ6731 (left) and [O I] λ6300 (right) brightness for the same model as in Figure 1. The $\log_{10}$ of the integrated intensity is plotted in units of erg s^{-1} cm^{-2} $ster^{-1}$.

and ambipolar diffusion, are among the most important radiative and physical processes intrinsic to the MHD flows that ionize and heat the gas. Many significant updates of physics in X-rays, hydrogen reactions and momentum transfer cross sections and coefficients of ambipolar diffusion, go into streamline-by-streamline computations of electron fraction, temperature and abundances of important species. The flow spans up to 8000 AU, right from where the wind is launched. This is the first *a priori* whole scale computation of thermal structures of MHD winds by self-consistent flow structure and processes that drive the winds.

Studies with the approach by Shang et al (2001) concluded that x-rays are capable of ionizing the base of the x-wind, and help maintain the ionization level at large distances, which are balanced by slow radiative recombination. This finding explains the profile of ionization in jets, which Bacciotti et al (1995) inferred phenomenologically from ground-based data with forbidden line ratios, but whose ionization source was not identified. Better analysis of Bacciotti & Eislöffel (1999, BE), applied to adaptive optics and HST/STIS data, indicated that the base of jets are significantly ionized with $x_{\rm e} \sim 0.01 - 0.4$ (Bacciotti 2001). The typical X-ray luminosity from an active YSO ionizes the x-wind flow at this level. However, for jets to be bright in the optical forbidden lines, maintaining $T \sim 5,000 - 10,000\,{\rm K}$ at thousands of AU from the stars with sufficient emitting areas, poses a difficulty for the internal heating sources due to powerful adiabatic expansion.

We also implemented a phenomenological model of wind heating based on stochastic shock dissipation, similar to MHD simulations of turbulence (e.g., Ostriker et al. 1999). The mechanical heating arises from fluctuations produced by the time dependent processes that are carried by the wind to large distances where they are dissipated in shocks, MHD waves, and turbulent cascades. This combines the local shock diagnostics that have long been applied to explain the complex emission spectra (see, e.g., Hartigan, Bally, Reipurth, and Morse 2000), and the global properties of the jets that seem closely connected to the activities of the exciting sources. Applied to a time-steady flow, the time-averaged effect of heating can be expressed by the scale-free volumetric heating rate, $\Gamma_{\rm mech} = \alpha \rho v^3 s^{-1}$, where ρ and v are the local mass density and flow speed, and s is the distance from the origin. In particular, α is a phenomenological constant, whose magnitude characterizes the strength of the disturbances. When a partially-revealed but active YSO is considered, $\alpha \sim 10^{-3}$ in the numerical calculations produces temperatures and electron fractions that are high enough for the x-wind jet to radiate in the optical forbidden lines at the intensity level and on the spatial scales that are observed (see Figure 1). Expressed in terms of velocity variations, such values of α imply a fractional velocity change of $\lesssim 5\%$, which suggests that the underlying background steady-state flow is relatively unperturbed.

Figure 2 shows the synthetic image made of the excitation conditions in Figure 1. Compared with the synthetic image of uniform excitation (which only illustrates the integrated column density out of 3-D flow cube), the appearance of conic shape at the base of the jet, as has been widely adopted as the "jet opening" in images, is a result of the self-consistent excitation pro-

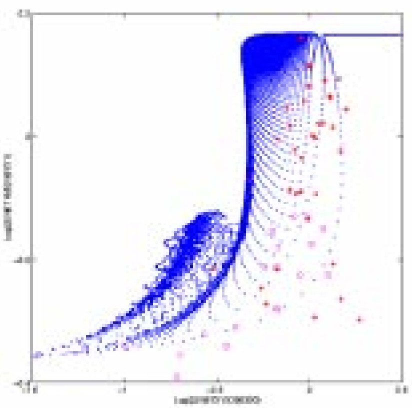

Fig. 3.— [S II] λ6716/[S II] λ6731 line ratio vs. the [S II] λ6731/[O I] λ 6300 based on the synthetic images in Figure 2, where the jet is viewed perpendicular to its axis.

file obtained by the phenomenological approach of heating. This illustrates the importance of self-consistent density and thermal profiles in the modelling scheme to capture the features in real images. The jet width extracted from Figure 2 is very similar to some jet widths obtained by HST and by adaptive optics (Dougados et al 2000).

The value of such diagnostics is best illustrated by cross line ratios from the optical forbidden lines. Figure 3 is the line ratio derived from Figure 2. Each blue point is a "theoretical" data point from each pixel. The stars are compiled from the HH objects available from ground-based data back in Raga et al (1996). The circles are DG Tau at resolution approaching $0.1''$ for the microjets (read from Fig.3 of Lavalley-Fouquot et al 2000). The synthetic line ratio plot of one single jet object, using x-wind model, could encompass the diverse excitation condition in most objects. The only points that fall outside of the theoretical domain actually come from strong shock emissions which cannot be explained in the current theory of weak shocks. Figure 3 provides the critical test for theoretical models to generate conditions that excite the observed lines, and opens up the window for new perspective of interpretation.

III. SUMMARY

In this short article, we summarized recent theoretical developments that lead to direct comparison with real data by first-principle modelling of MHD x-winds and physical processes occurring near the YSOs. We argue that at their base, YSO jets are optical illusions associated with the excitation mechanisms by which atomic forbidden lines are excited. Gentle time-variabilities or pulses implied by knots in observed jets mainly contribute to the variation of thermal excitation on top of background flow, whose densities and velocities are closely maintained by steady state values. This is a demonstration that, first-principle calculations of self-consistent physical processes in young stellar winds provide robust theoretical help on probing the jet phenomena.

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